Operation of the Far Ultraviolet Spectroscopic Explorer Mission[1]

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Abstract—The Far Ultraviolet Spectroscopic Explorer (FUSE) mission, launched 24 June 1999, is a NASA Origins program designed to provide an observatory for far ultraviolet spectroscopy with ~ 1 arcsec pointing for use by the broad astronomical community. Each year about 600 individually planned targets are observed with a total on-target time of approximately 9 million seconds. FUSE was developed and is operated with a cost cap. Cost considerations also led to the selection of a low-earth orbit over a high-earth orbit, which as a by-product increased the complexity of operation. Thus, FUSE is a general-use astronomical observatory, operated in low-earth orbit with a cost cap.

This paper describes the approach used in developing the FUSE ground system. The resulting operations system is effective, robust and flexible. We also discuss satellite performance, our success in overcoming hardware breakdowns, and plans for operations in the extended-mission phase, which will have additional resource constraints.

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1. INTRODUCTION

The FUSE mission is designed to serve as an observatory class facility in space for use by the broad astronomical community. It is a NASA *Origins* program with additional support from the Canadian Space Agency and the Centre National d'Études Spatiales of France.

The instrument consists of four co-aligned telescopes feeding four spectrographs that collectively cover the range 90.5 nm to 118.7 nm with a spectral resolving power of ~20,000. The data are used for a wide range of scientific investigations ranging from studying deuterium, a fossil nucleus left from the Big Bang, to the nature of the diffuse gas between galaxies. The instrument is sufficiently

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sensitive that FUSE observations complement Hubble Space Telescope (HST) measurements, which are obtained above 117 nm. In order to be scientifically useful, the data must be precise. The photometric calibration is good to 10% and the wavelengths are determined with a precision of 0.003 nm, equivalent to 30 microns on the detectors. Each year about 600 different targets are observed with a total on-target time of approximately 9 million seconds. Each observation must be individually planned with suitably tailored acquisition sequences and a unique star catalog for autonomous pattern recognition by the satellite.

The instrument is mounted on a spacecraft bus developed by the Orbital Sciences Corporation. It supplies power, telemetry and attitude control. Three-axis stabilized attitude control is augmented by information from a Fine Error Sensor (FES) camera on one of telescopes. This attitude information is used to place the target in the spectrograph entrance aperture to ~ 1 arcsec, and reduces pointing jitter and drift to < 1 arcsec during the observation. The satellite is operated from a Satellite Control Center (SCC) on the Homewood Campus of the Johns Hopkins University via a ground station at the Mayaguez Campus of the University of Puerto Rico. Figure 1 shows the FUSE satellite in a clean room at Cape Canaveral Air Force Station, shortly before launch on 24 June 1999.

The FUSE program was restructured in 1994. This included a more than a two fold reduction in the development costs and reorganization of the mission with the principal investigator assuming responsibility for managing all segments of the mission except launch. The primary scientific goals and most of the instrumental capability were retained. See [1] for a more detailed discussion of the restructuring process. As a consequence of the restructuring, FUSE was developed with a cap on all costs [1], including those for post-launch operations. The cost cap during development led to the choice of a circular low-earth orbit of 765 km at an inclination of 25 degrees, which increased the complexity of operations compared to operations in the high-earth orbit under consideration prior to the restructuring. Hence, part of the challenge for the FUSE program was to develop a low-earth-orbit observatory for general use that could be operated at a modest cost.

FUSE was developed and is operated as a Principal Investigator (PI) class mission[1]. The Johns Hopkins University (JHU) led the development team and is responsible for the operation of the mission, with oversight by the NASA's Goddard Space Flight Center. In addition to the oversight role, NASA was responsible for the Delta II launch. This management structure has permitted more flexible and decisive approaches to solving the constraints associated with the cost caps in the development and mission-operations phases.

Figure 1. The FUSE satellite mounted on the attachment ring for the Delta II launch vehicle. The spacecraft bus, which occupies the lower 0.9 m of the satellite package, provides power, attitude control, and S-band communication. The omni-directional antennas are located just below the instrument-spacecraft interface. The upper package contains the four telescopes, each feeding a separate spectrograph. The satellite package, less the launch vehicle payload attach fitting, is 5 m in length and has a mass of 1335 kg. Photo: NASA.

As a PI-class mission, much of the observing time during the early part of the mission was allotted to the PI team. However, slightly more than half of the observing time during the three years of the Prime Science Mission phase has been assigned to Guest Investigators selected by NASA. All of the observing time will be available to Guest Investigators when the Extended Mission phase begins in April 2003.

Two types of major hardware anomalies have occurred in the attitude control system. First, in 2001 November and December, the number of functioning reaction wheels was reduced from four to two. Secondly, the ring-laser gyroscopes have degraded since launch. Thus, the attitude control system may have to operate in the future with reduced gyroscope information, relying more heavily on the FES. Both types of anomalies require significant modifications to flight software and increase the complexity of operating the satellite.

For an overview of the FUSE mission and its on-orbit performance, see [2] and [3]. A recent discussion of FUSE observatory operations for the astronomy community has been presented in [4]. Additional information about the FUSE mission is available at http://fuse.pha.jhu.edu/.

This paper will discuss the construction and operation of the FUSE ground system and the performance of the system since launch. In section 2 we will describe the challenges faced in developing and operating the FUSE mission. Section 3 will discuss the responses to the challenges. They were both technical and managerial in nature. The operations system has been effective and robust against problems as shown by the mission performance to date presented in section 4. Section 5 discusses the response to hardware anomalies in the attitude control system and section 6 presents the plans for operating in the extended-mission phase with additional resource constraints. Section 7 concludes with a brief summary.

2. CHALLENGES TO IMPLEMENTATION AND OPERATION

In comparison with NASA's "Great Observatories" such as HST and the Chandra X-Ray Observatory, the FUSE project is modest in size. However, as a general use observatory it must perform the same functions for the astronomical community: management of observing programs, science timeline planning, daily observatory operations, data processing and archiving of the final scientific data products. The operations team is a mixture of about 40 JHU staff personnel, contractors, scientists and engineers located primarily at JHU. Figure 2 outlines the process from ingestion of an individual phase 2 proposal to delivery of the data to the Multimission Archive at the Space Telescope Science Institute (MAST) for access by the scientist responsible for analyzing the data.

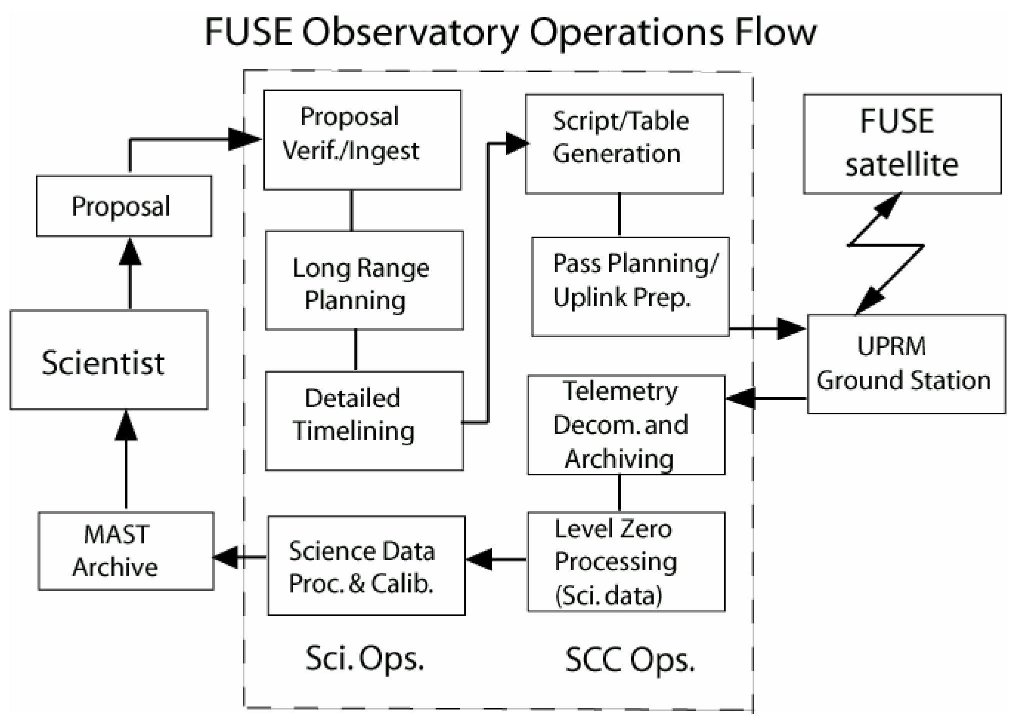

Figure 2. Process flow in the operation of the FUSE observatory. Prior to this process and not shown in the figure, scientific proposals are evaluated and selected by NASA or the PI team. After selection of a proposal, the lead scientist submits a Phase 2 Proposal to the FUSE operations center in Baltimore. See the box labeled "Proposal" in the upper left hand corner of the figure This proposal contains the astronomical information necessary for planning the observation. As shown in the column of boxes above the label "Sci. Ops." the planners in Science Operations schedule the observations and provide a mission-planning schedule with sufficient information to generate a script for uploading to the satellite for the Satellite Control Center (SCC) operations team. See the column above "SCC Ops." The data resulting from the observations are downloaded to a ground station at the University of Puerto Rico, Mayaguez (UPRM). After transfer to Baltimore, it is processed and sent to the MAST archive for access by the scientist. From [4].

The FUSE observatory performs many individual observations, each requiring a customized satellite operations script. The resulting requirements ripple through the operations system. The number of planners required is much larger in comparison to an all-sky mapping mission. Satellite operations also require more people and even the data processing is more complex because of the variety of modes in which data are acquired.

Prior to the restructuring in 1994, FUSE was envisioned to be in a high-earth orbit. Being far from Earth, operations were expected to be simple and efficient, with much of the sky available for viewing at any time. Near continuous communications with the satellite would have been possible, minimizing onboard command loading and data storage requirements, allowing real time target recognition and acquisition, and providing rapid ground response both to new astronomical events and problems or failures. Both the flight software and ground system would be simple since the SCC staff would be responsible for decisions and for redirecting activities if necessary.

During the restructuring, because of concern with the mission cost cap, the orbit was changed to low-earth. This removed the requirement for an extra engine for the launcher, reduced mass constraints and lowered the design radiation dosage. However, selecting a low-earth orbit increased the complexity of operating an observatory satellite. Typically, due to occultation by the Earth, a target is observable for a little more than 2000 s out of a 6000 s orbit. In addition to the initial acquisition of a target, the observation must be stopped during occultation and a reacquisition at the end of occultation planned for each orbit. Planning must also take account of when the satellite orbit passes through the South Atlantic Anomaly because the large flux of high-energy particles prevents data acquisition.

Concerns about hardware costs, operational costs, and mass forced reliance on a dedicated ground station rather than NASA's Tracking and Data Relay Satellite System (TDRSS). The spacecraft must operate autonomously with only ~12 minute contacts every 100 minutes six to seven times a day, and then a complete blackout for about half of every day. It is usually out of contact when acquiring targets or performing other critical observatory operations. The onboard software has to handle a variety of contingencies and events, autonomously recovering from problems, while managing health and safety concerns. In addition, the half-day blackout requires careful management of the recorder memory and restriction of high data rate observations during the blackout period.

The FUSE project faced the challenge of developing techniques and tools that would keep the size of the science operations staff within the scope of the mission while still permitting accurate planning of the complex timelines. Despite the increased complexity of operations in low-earth orbit, the mission cost constraints meant that the development costs for the ground system software were also constrained.

Another consequence of the cost capped mission was acceleration of the development schedule beginning in December 1995. Testing of the integrated satellite system and ground system started in October 1998 and the satellite was launched in June 1999. The post-launch operations phase was also cost capped. This limited the amount of unfinished development work that could be passed on to the post-launch phase.

3. SOLUTIONS TO THE CHALLENGES

There was no unique solution that solved all of the challenges discussed in section 2. Rather, there were many. They can be loosely grouped as Technical Solutions and Management Solutions. We will discuss both types with an emphasis on the former.

3.1 Technical Solutions

FUSE satellite operations are highly autonomous. During nominal science operations it is controlled by software scripts, uplinked to the spacecraft bus and loaded into the Instrument Data System (IDS) computer. Typically, the IDS carries scripts for approximately a 24-hour period. The IDS sends commands to the spacecraft attitude control system (ACS) in order to slew to a target for acquisition. The FES camera mounted on one of the telescopes provides a 20 arcmin wide image of the star field. The IDS then uses pattern recognition to locate the position of the target relative to the spectrograph aperture by employing a small star catalog tailored for each target and uploaded as part of the command load. The IDS then commands the ACS to perform small slews to center the target in the aperture. After acquiring the target, the FES updates the ACS through the IDS every second in order to reduce jitter and drifts in the pointing. Overall jitter is ~ 0.6 arcsec rms. The scripts also control the time when a reacquisition will start after Earth occultation and the number of orbits for the observation before going on to the next scheduled target.

The Low Earth Orbit Terminal (LEO-T) ground station is an autonomous 5-meter antenna. Routine maintenance is provided by one engineer at the University of Puerto Rico-Mayaguez. Commands for uploading and telemetry from satellite dumps are stored on-site at Mayaguez. Commands are transmitted to Mayaguez from the SCC in Baltimore and data are returned via ISDN data circuits and the Internet2. In addition to about seven 12-minute contacts per day with the LEO-T, several additional contacts are possible when needed using a commercial station (Universal Space Network) in Hawaii. The mission was designed without a TDRSS transponder. However, prior to launch, NASA developed the capability for non-TDRSS compatible spacecraft such as FUSE to communicate with the system using its S-band omni-directional antenna. The date rate is low, < 32 kbits s^{-1}, but this access gives coverage when needed for health and safety, recovery from hardware anomalies, or other special operations.

The ground system software in the SCC and the IDS flight software both use the Spacecraft Command Language (SCL) developed by Interface & Control Systems, Inc. The FUSE project supported development of capabilities that permitted application of SCL to the FUSE mission. SCL is a high level language that provided significant flexibility both in the development phase, and when necessary, for post-launch changes.

One important distinction between the FUSE mission and many others has been the necessity to modify flight and ground software during the mission in response to conditions on-orbit. This was approached with caution, but has been essential to the mission performance. For the ground system and the IDS, the use of SCL eased some of the changes. However, in all cases, the changes to flight software required extensive testing with simulators before uploading as well as in-flight testing.

Commercial Off-the Shelf (COTS) products were used as sub-modules where appropriate in the ground system software. Combined with SCL, COTS products were invaluable in a cost and schedule constrained environment. The development of the ground system software in the SCC has been discussed by Calk and Silva [5].

Software packages developed for other NASA programs were adapted and modified. The data pipeline uses a version of the OPUS telemetry processing system developed by the Space Telescope Science Institute (STScI). Only the data calibration portion had to be written specifically for FUSE data. The SPIKE planning and scheduling software developed at the STScI was adapted for long range planning of FUSE observations. In the same spirit, we resisted the temptation to build the FUSE archive at JHU and utilized the MAST archive at the STScI. Because users download directly from the MAST archive, the distribution of data on hard media is not required.

3.2 Management Solutions

The project began a study of how to construct and operate a cost constrained ground system as soon as the restructuring of the FUSE mission began in September 1994. It did not wait for the development phase to begin in the late autumn of 1995 or for launch minus 1 year, which is too common. Thus, there was ample time to think out novel technical solutions and to recover from mistakes before they became expensive.

Experienced personnel were put in place for the key positions early. The Mission Operations Manager, Flight Operations Manager, Science Operations Manager and Chief of Mission Planning were all in place within eight months after the start of the development phase, almost three years prior to launch. This had an important effect on the maturity of the technical decisions made early in the development process. Likewise the high level of experience of the operations staff has been crucial in the post-launch operations phase.

The developers of the ground system software from Interface & Control Systems, Inc. and the Flight Operations Team from Honeywell Technology Solutions Inc. were collocated at JHU during development. This improved communication and permitted rapid solution of problems as they arose in testing. For similar reasons, the participation of ground system personnel, both from science operations and from flight operations, in the integration and testing of the satellite benefited the development of the ground system. Some of this participation was through mission simulations when the software in the SCC was used to control the satellite while under test at GSFC. Also, individual personnel simply aided the integration and testing of the satellite as needed, gaining broader experience and additional insight to the operation of the satellite.

4. MISSION PERFORMANCE

In-Orbit-Checkout and Science Verification of the mission required about 120 days to complete, 30 days longer than the prelaunch plan. This was due in part to considerable caution about outgassing from the composite structure, and its potential to harm the detector and degrade the optical reflectivity. Caution in this area both before and after launch appears to have paid off; the instrument sensitivity has degraded less than about 20% over the mission to date (December 2002), much less than the prelaunch predication of 20% per year. An additional source of delay was the discovery of thermally induced drifts in co-alignment of the four telescopes and in the spectrographs. Modeling of the data showed that the alignment was a slowly varying function of the sun and the orbit pole angles. This was dealt with by grouping the observations and scheduling them in broad sun-angle and pole-angle bins. Dedicated realignment activities are scheduled about every two weeks, more frequently if science operations require observations at very different sun-angle or pole-angle orientations. Although this solution managed the alignment anomaly, it puts an additional burden on science operations planning. However, the ground system is flexible enough to incorporate these constraints to mission planning with changes in both short-range and long-range scheduling software. Early Release Observations for dissemination to the astronomical community began on 1 November 1999, and the Prime Science Mission on 1 December 1999.

FUSE has acquired 25 Ms of scientific data on more than 1600 different astronomical targets to date (December 2002). The overall observational efficiency (photon gathering time on scientific targets over wall-clock time) is over 29%. The prelaunch estimate was 25%, which did not include the additional overhead for channel alignments. Thus, this is an excellent efficiency for a low-earth orbiting observatory. However, the best indicator of success for a mission of this type is scientific productivity. Limited space prevents discussion of the scientific results. We note that there are over one hundred refereed publications in scientific journals based on FUSE observations and the number is growing rapidly.

One important lesson learned was the critical dependence of mission performance on staffing level. A space observatory such as FUSE, with a given set of software that determines the degree of automation, requires a certain minimum number of people to operate efficiently. A small change in the number of personnel, particularly in satellite operations or planning, can have dramatic effects on the observing efficiency. This was demonstrated at the start of the prime mission, when the observing efficiency was unacceptably low. A small increase in staff, 4 full time equivalents, led to a dramatic increase in observing efficiency that has held through the rest of the mission. However, there is great uncertainty in predicting the critical level accurately ahead of time. Finding the optimal level is a highly empirical process.

5. RESPONSE TO POST-LAUNCH ANOMALIES

The ground system has proven to be robust against several satellite hardware anomalies that could have affected mission performance. Section 4 discusses the effects of thermal misalignment, discovered early in the mission. More recently, anomalies in the ACS reaction wheels and gyroscopes have become important.

The FUSE satellite carries four reaction wheels, one along each orthogonal axis and a fourth skew wheel that served as a backup and simplified zero momentum biasing. During late November and early December 2001, two (out of four) reaction wheels (pitch and yaw) stopped functioning. At that point, attitude control about three axes was not possible. The technical solution, put in place within seven weeks, was to incorporate the Magnetic Torque Bars (MTB) into the ACS control loop with the two remaining wheels [6]. This led to a dramatic recovery of the satellite's scientific capability. It is believed that the failure of the two wheels was due to a thermal environment that exacerbated a tight tolerance between the wheels and their housing. The remaining two wheels (roll and skew) are mounted in more benign thermal environments and are considered much less likely to fail.

The reliance on MTBs adds significantly to the complexity of satellite operations. The MTBs were initially designed only to manage excess reaction wheel angular momentum and their torque is about ten percent of that of a reaction wheel. In some orientations, this is insufficient to overcome gravity gradient torques, the major disturbance at this altitude. In addition, MTBs can provide torques with vector directions perpendicular to the terrestrial magnetic field, but not along it. Finally the Earth's magnetic field strength and direction varies significantly with location about the orbit, the 24-hour period rotation of the Earth, and the 60-day precession of the orbit. After initial implementation of the new control loop, about forty percent of the sky was available for observations. Empirical testing, modeling, and the development of new planning tools have opened up the sky coverage to 75% of the sky [4]. A major barrier against further improvements is a restriction against pointing into the ram direction (i.e. along the satellite velocity vector) in order to protect the mirror coatings. As solar activity decreases, the atmospheric density at 765 km altitude will decrease by one to two orders of magnitude. Coupled with additional operational improvements, we are optimistic that near 100% sky coverage will be achieved by late 2003. Figure 3 compares the time available in different parts of the sky over a one year period using the techniques available in the spring of 2002, with the situation expected in late 2003 after improvements in ACS software, new planning techniques, and access to low ram-angle attitudes permitted by the expected decrease in the atmospheric density.

The satellite carries six ring-laser gyroscopes (RLG); two are mounted along each orthogonal axis. A major concern is the monotonic decrease in laser intensity with time. The RLGs appear to work well up until the point where the laser gain falls below its losses and laser oscillation stops. The laser intensities cannot be monitored except for a single flag that trips at a level that is typically half of the initial intensity. As of this date (December 2002), the laser-intensity flag has tripped on all of the gyroscopes except for one along the yaw axis. One RLG along the roll axis ceased functioning in May 2001 after a little more than two years of operation, including preflight testing. As a consequence, no redundancy exists on this axis and the remaining RLG shows a laser-intensity flag. To mitigate this problem, the flight software packages in the ACS, IDS and FES are being modified to permit operation with functioning gyroscopes along three, two, one, or zero axes [6]. The new flight software is in ground testing and will be loaded onto the satellite for in-flight testing in early 2003.

The gyroless control system is a considerable departure from the current satellite operations. Briefly, once a target has been acquired, the attitude information from the FES is the most accurate and always controls the attitude solution, even if there is no gyroscope information along one or more axes. During occultation or during slews, attitude is determined from a combination of gyroscope and Three-Axis Magnetometer (TAM) data. The most difficult state is the transition between these modes when a target is acquired (or reacquired). The initial acquisition on any star

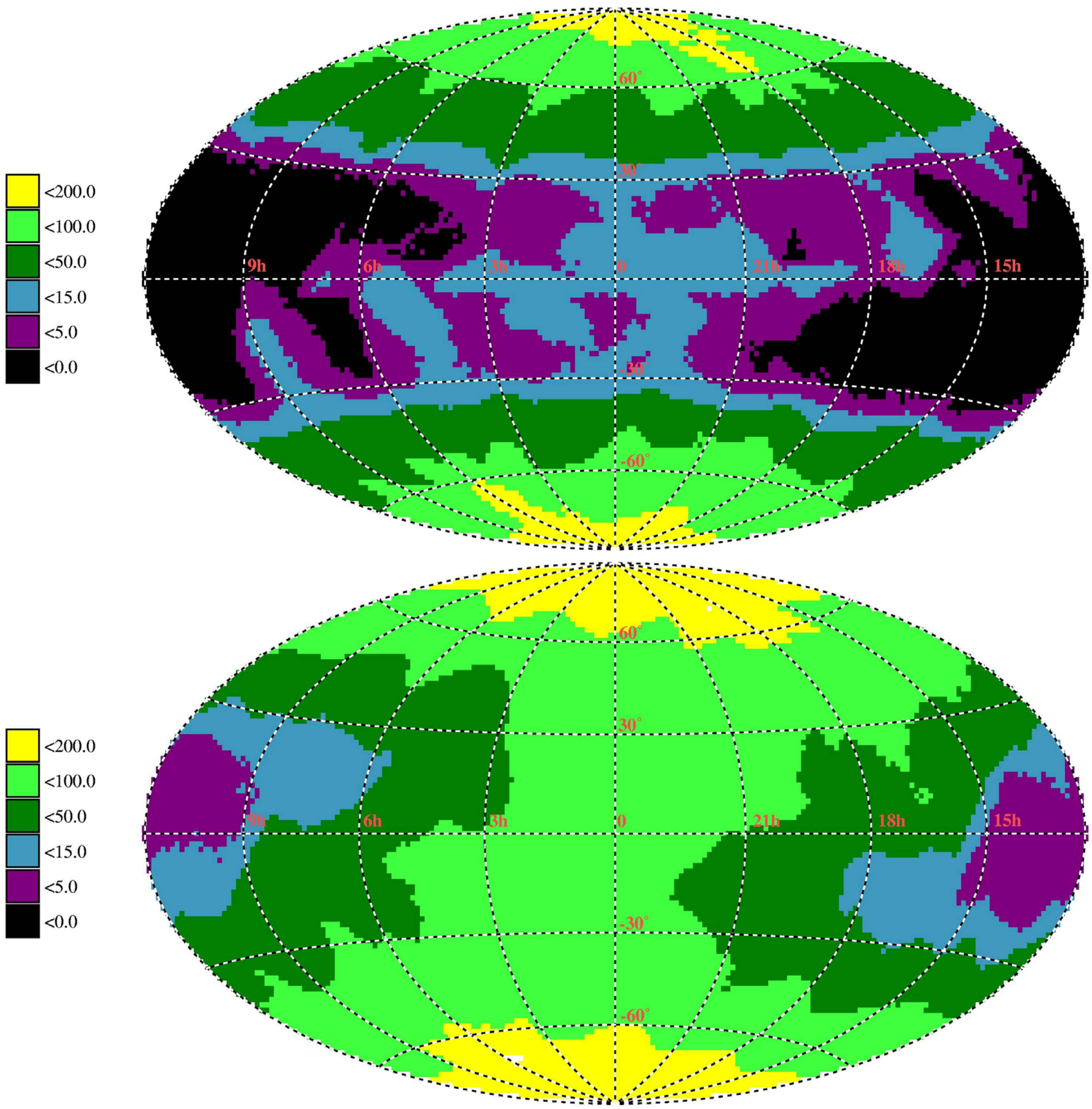

Figure 3. FUSE observing sky availability over a 12 month period for May 2002 versus that expected in late 2003.

The colors correspond to the maximum integrated amount of time in days (14.4 orbits per day) of observatory activity that are possible in a given part of the astronomical sky over a 12 month period. Upper panel: Availability in May 2002. Ram angle > 20 degrees, non optimized use of the MTB. Lower panel: Availability expected in late 2003. Ram angle = 0 degrees, optimized use of the MTB, roll adjustments to improve the orientation with respect to the magnetic field. Coordinates are right ascension (hours) and declination (degrees). A moon avoidance angle of 10 degrees and a sun angle of 85 to 150 degrees are assumed. The availability changes slowly from year to year, so the particular time period used for the estimate, in this case 1 May 2003 – 1 May 2004, is not critical. (Figure courtesy of Bryce Roberts, JHU.)

in the FES 20 arcmin field must be very rapid, because the drift rates are predicted to be in the range of 10 arcsec s^{-1}. Because of the uncertainties in pointing associated with the use of TAM data, the star table loaded to the IDS for pattern recognition must cover a region ~ 2 degrees in radius, about 16 times as large an area as that covered by the present tables. The overhead on observing time associated with the acquisition and reacquisition each orbit depends on how many axes have lost gyroscope information. It is expected to be small in comparison to the nominal observing period of 2000 s per orbit.

6. EXTENDED MISSION OPERATIONS

Due to the time lost to reaction wheel anomalies, the end of the Prime Science Mission has been extended from 30 November 2002 until 31 March 2003. NASA Senior Science Reviews in 2000 and 2002 have recommended an Extended Mission phase. NASA has accepted these recommendations and instructed the project to submit plans for operations through FY 2006 with reduced resources. FUSE is already a cost constrained mission. As part of a study for the Extended Mission, we found that large cuts in the number of personnel would likely produce an unacceptable reduction in observing efficiency. Large reductions in cost are not feasible when the operation is already quite lean. However, the further automation of the FUSE ground system presented by Calk [7] will lead to modest reductions in staff because many procedures such as ground station passes and SCC operations will be automated as much as possible. In addition, while maintaining all of the critical scientific capabilities of the satellite, the planned observing time has been reduced from 9 Ms to 7 Ms per year for the Extended Mission. However, as discussed in section 4, there is a critical point at which staffing levels can lead to precipitous drops in mission efficiency. The challenge for the project in the future is to find the proper balance and to work with the astronomical community to optimize the observing procedures for the highest scientific productivity.

7. SUMMARY

This paper discusses how the FUSE operations team met the challenge of developing and operating a low-earth-orbit astronomical observatory in a cost-constrained environment. The mission has good observing efficiency and high scientific productivity. The ground system is resilient and flexible in dealing with anomalies. Ultimately, such a system relies on the people who staff it. The success of the system is a tribute to their talent, creativity, and dedication.

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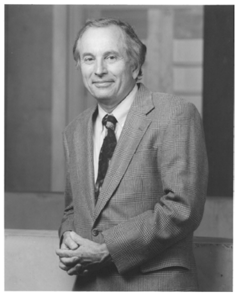

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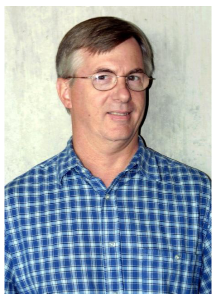

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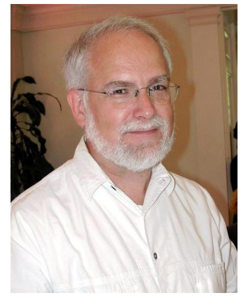

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